EFFECTS OF ELECTRON BEAM LOADING ON AN OPERATING PIEZOELECTRIC TRANSFORMER*

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Abstract

Piezoelectric transformers (PTs) are currently being used to accelerate charged-particle beams for various applications [1, 2]. Beam interactions at the output of the PT can be treated as a parallel RC electrical load. The impedance of the load can affect the output voltage due to the small, finite amount of charge available in the PT. High output voltages necessary for beam acceleration cannot be achieved if the current output from the PT is too high. A thermionic electron emitter was used to provide a controllable beam current for testing the effects of electrical loading on the PT. The electron beam was operated in vacuum pressures of 10^{-6} - 10^{-5} Torr. Variations in the electron beam current were used to vary the resistive portion of the load while beam distance was used to vary capacitance. The effects of such variations were measured via bremsstrahlung interactions at the output electrode of the PT to determine output voltage and optical techniques for finding internal operating parameters such as electric field.

I. INTRODUCTION

The piezoelectric effect is a commonly used phenomenon for many actuators or sensors [3, 4]. By combining the piezoelectric and inverse-piezoelectric effects, a low amplitude input voltage can be converted to a large amplitude output voltage using a piezoelectric transformer (PT). A PT can be used to step voltages up or down, but, unlike a traditional transformer, no mutual magnetic flux linkage is required [5, 6]. A length-extensional PT has an applied electric field across the thickness of the crystal which results in a longitudinal mechanical vibration. The mechanical vibration produces a high electric field in the output section of the crystal due to the piezoelectric effect [6, 7]. Transformers in this design have compact sizes, low mass, and high efficiencies [6].

Although many investigations have been performed to maximize the transformer ratio of length-extensional piezoelectric transformers, these studies have typically been performed for discrete component loads [8-10]. Additionally, these PTs had voltage transformation ratios of less than a few hundred [5, 9]. Acceleration of charged particle loads require output voltages of at least tens to hundreds of kilovolts [11]. Previous studies using PTs to accelerate charged-particle beams did not focus on the PT internal operation for these loads.

This paper presents modeling and experimental results that analyze the effects of a thermionically emitted electron beam as a load at the output of the PT. Measurements of the input mechanical and output electrical quality factors are presented. Additionally, an optical diagnostic was used to measure the internal stress and electric field based on the electro-optic and photoelastic effects.

II. EXPERIMENT SETUP

A piezoelectric transformer was operated in a vacuum chamber with a thermionic filament to produce bremsstrahlung and fluorescence x-rays. A brief description of an optical diagnostic used to analyze the operation of the PT is also discussed.

A. Piezoelectric Transformer

An example of the PTs used in this paper is shown in Figure 1. The PT was made from a 135 degree rotated y-cut crystal that was 100 mm long, 10 mm wide, and 1.5 mm thick. Fifty percent of the surface at one end of the crystal was covered on each side with a conductive silver paint to create the two input electrodes. The silver

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14. ABSTRACT
Piezoelectric transformers (PTs) are currently being used to accelerate charged-particle beams for various applications [1, 2]. Beam interactions at the output of the PT can be treated as a parallel RC electrical load. The impedance of the load can affect the output voltage due to the small, finite amount of charge available in the PT. High output voltages necessary for beam acceleration cannot be achieved if the current output from the PT is too high. A thermionic electron emitter was used to provide a controllable beam current for testing the effects of electrical loading on the PT. The electron beam was operated in vacuum pressures of 10-6 - 10-5 Torr. Variations in the electron beam current were used to vary the resistive portion of the load while beam distance was used to vary capacitance. The effects of such variations were measured via bremsstrahlung interactions at the output electrode of the PT to determine output voltage and optical techniques for finding internal operating parameters such as electric field.

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Figure 1. Picture of the lithium niobate piezoelectric transformer. The PT is 100 mm long, 10 mm wide, and 1.5 mm thick.

paint was also used to attach wires to these input electrodes. An output electrode with a surface area of 25 mm^2 was painted onto the opposite end of the crystal and lead filings were placed into the paint for enhanced bremsstrahlung conversion.

B. PT with an Electron Beam Load

The PT was operated in a vacuum chamber between 10^{-6} – 10^{-5} Torr. The input signal was a 10 V amplitude voltage at approximately 62 kHz with 3,000 cycle bursts on a 1 s burst period. Input currents had amplitudes of approximately 100 mA. The 62 kHz input signal resulted in a mechanical vibration at the second harmonic frequency for the particular PT geometry. The output voltage had a much greater voltage due to the piezoelectric effect within the lithium niobate. Step-up voltage transformer ratios in excess of 2,100 were observed for these experiments.

A thermionic filament made of 3% rhenium doped tungsten alloy was heated using DC currents between 2.0 to 2.5 A_{DC}. Thermionic emission current was accelerated by the electric fields generated by the output of the PT on one half-cycle of operation. This configuration is shown in Figure 2. Incident electron energy was attenuated by the silver paint output electrodes and the lead filings attached to the output electrodes, yielding bremsstrahlung radiation. Experimentally measured endpoint x-ray energies of 17 keV were observed for a 2.3 A_{DC} filament current, corresponding to a PT output voltage of 17 kV.

A general electron beam load can be modeled as a parallel resistive-capacitive (RC) load as shown in Figure 3. Simulated profiles for the magnitudes of internal stress, electric field and electric potential are shown in Figure 4 for an arbitrary low-current, thermionic current resistance of 10 GΩ and a capacitance of 0.05 pF with a PT mechanical quality factor of 10,000. A top-down view of the PT is shown in Figure 4a for reference. Points of

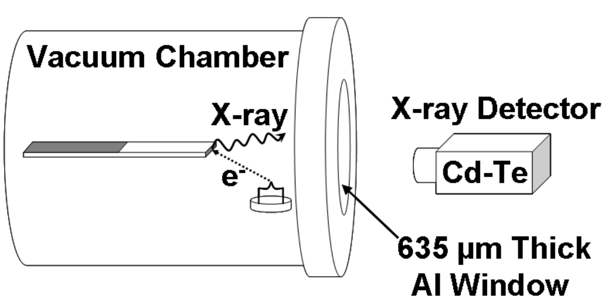

Figure 2. Diagram of the thermionic filament with a PT in the vacuum chamber. X-rays are detected outside the vacuum chamber through a 635 μm (0.050”) thick aluminum window with a cadmium-telluride x-ray detector.

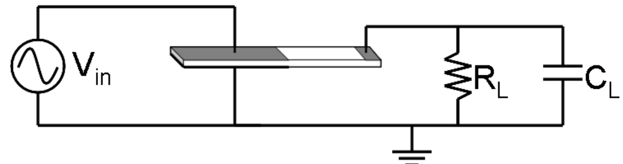

Figure 3. PT with a parallel resistive and capacitive load.

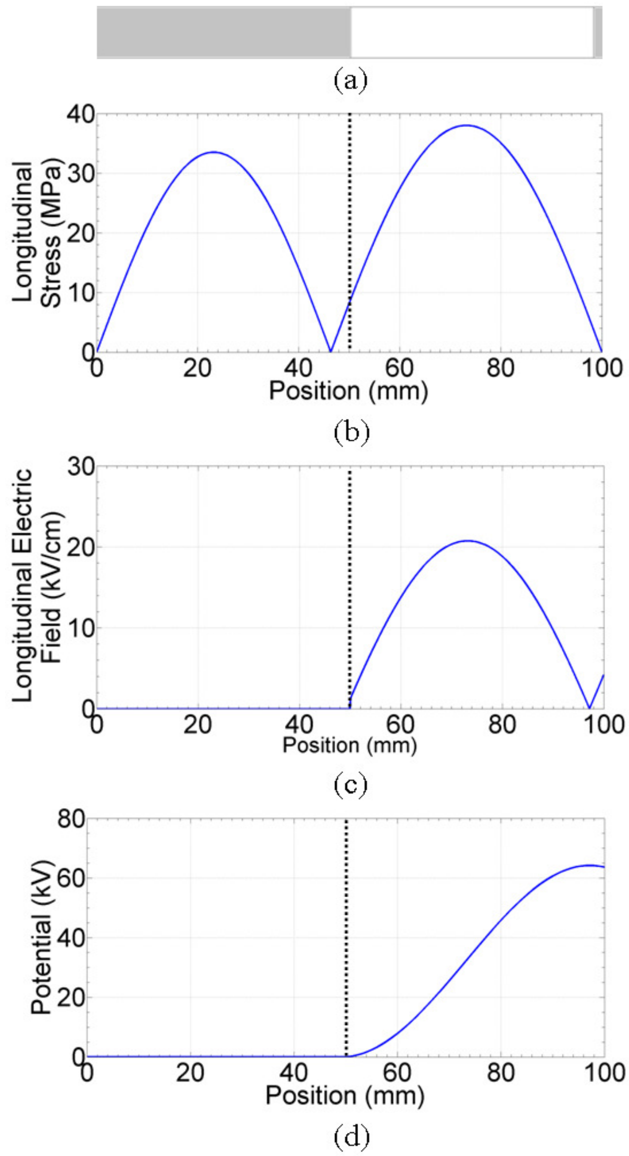

Figure 4. Simulated profiles of internal PT parameters for a parallel 10 GΩ, 0.05 pF load with an input mechanical quality factor of 10,000. Dotted lines correspond to the end of the input electrodes. (a) Top-down view of PT for comparison with waveforms. (b) Simulated longitudinal stress along the PT. (c) Simulated longitudinal electric field along the PT. (d) Simulated electric potential along the PT.

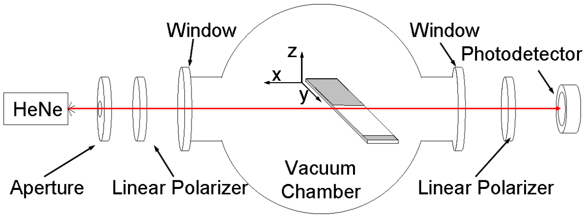

Figure 5. Optical diagnostic setup. Laser beam propagates through width of PT in $-\hat{x}$ direction. The electro-optic and photoelastic effects change the index of refraction of the lithium niobate in the *y-z* plane.

maximum stress correspond to vibrational null points along the PT. The output electrode does not necessarily correspond to the maximum electric potential as shown in Figure 4d. The electric field and electric potential profiles are dependent on the load impedance.

C. *Optical Diagnostic Setup*

The setup of the optical diagnostic that was used to measure the internal stress and electric field within the PT is shown in Figure 5. A helium-neon (HeNe) laser with a wavelength of 632.8 nm was used as the light source. A linear polarizer was used to ensure that the beam was linearly polarized as it entered the PT. As the beam propagated through the PT, the electro-optic and photoelastic effects changed the indices of refraction in the y and z directions as the axes are denoted in Figure 5. The beam that exited the crystal had an elliptical polarization due to the optical phase shift that occurred between the y and z wave components. Passing the beam through a second linear polarizer resulted in light-to-dark transitions at the photodetector for every $\pi/2$ phase shift that occurred.

The phase shifts were assumed to be continuous for the time-harmonic stress and electric field within the PT. The total phase shift for a quarter of an input voltage period was used to determine the magnitudes of the electric field and stress within the crystal based on the optical indicatrix and piezoelectric constitutive equations shown in (1) and (2) where S is strain [unitless], s is elastic compliance coefficient [m^2/N], T is stress [Pa], d is piezoelectric strain coefficient [C/N], E is electric field [V/m], D is electric flux density [C/m^2], and ε^T is the permittivity for constant stress [F/m].

$$\{S\} = \{s\}\{T\} + \{d\}^t\{E\} \tag{1}$$

$$\{D\} = \{d\}\{T\} + \{\varepsilon^T\}\{E\} \tag{2}$$

III. RESULTS

A. *Quality Factor Analysis*

The electrical and mechanical quality factors (Q-value) were measured for a resonating PT with an electron beam load. Figure 6 shows the frequency sweep of the input voltage that was used to calculate the Q-values based on (3) where Q is the Q-value [unitless], $f_{resonant}$ is the resonant frequency [Hz], and Δf_{3dB} is the full-width, half-maximum of the measured values [Hz]. The load for measurements taken in Figure 6 was an electron beam produced by a thermionic filament with a 2.3 A_{DC} filament current. The input mechanical Q-value was based on the electrical input impedance and was measured to be 3,743. The output electrical Q-value was based on the PT voltage transformation ratio and was measured to be 3,251.

$$Q = \frac{f_{resonant}}{\Delta f_{3dB}} \tag{3}$$

Figure 7 shows the simplified electromechanical equivalent circuit as determined by Rosen's initial work with length-extensional piezoelectric transformers [5]. The resistance, R, is the internal mechanical resistance of the PT, while aR and bR are the effective impedances of the generator and load, respectively. The Q-values are related using (4), where Q_e is the effective output electrical Q-value and Q_m is the input mechanical Q-value [5].

$$Q_e = \frac{Q_m}{1 + a + b} \tag{4}$$

B. *Optical Diagnostic Results*

The optical diagnostic setup from Figure 5 was used to measure the longitudinal stress and electric field based on the change in the indices of refraction. The results from optical diagnostic are shown in Figure 8 and Figure 9 for

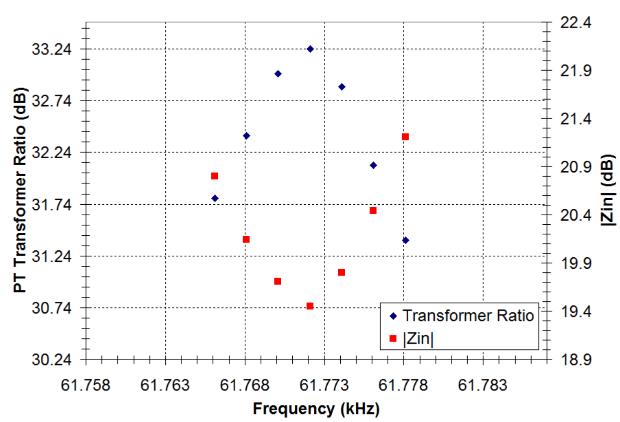

Figure 6. Frequency sweep of the PT input voltage to determine the mechanical and electrical quality factors for the PT with a thermionic filament operating at 2.3 A_{DC}. The mechanical and electrical quality factors were determined to be 3743 and 3251, respectively.

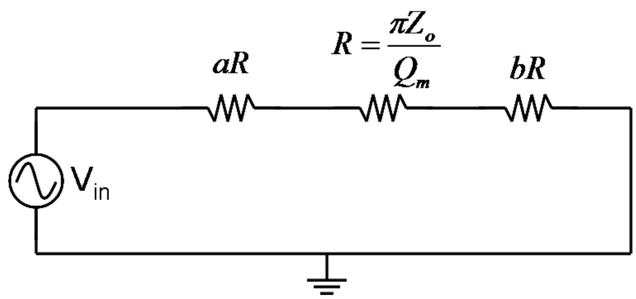

Figure 7. Simplified electromechanical equivalent circuit.

the stress and electric field, respectively. A thermionic filament current of 2.3 A_{DC} was used to generate the electron beam, and an output voltage of 17 kV was measured based on the endpoint x-ray spectrum energy.

Due to the limited diameter of the vacuum chamber windows, only the last 25 mm of the PT could be measured. A maximum stress of approximately 10 MPa was measured within that 25 mm range, while a maximum electric field of approximately 5 kV/cm was measured. Simulated profiles of stress and electric field are also shown in Figure 8 and Figure 9. The simulated parallel RC load from Figure 3 was a 10 GΩ resistor and a 0.04 pF capacitance.

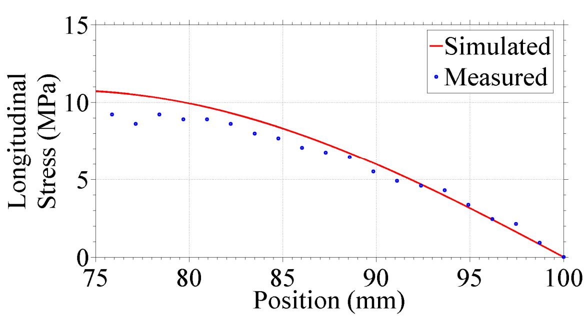

Figure 8. Simulated and optically measured longitudinal stress magnitudes in the PT. Only the last 25 mm were measured due to the size of the vacuum chamber window. Simulated parameters correspond to a parallel 10 GΩ, 0.04 pF load.

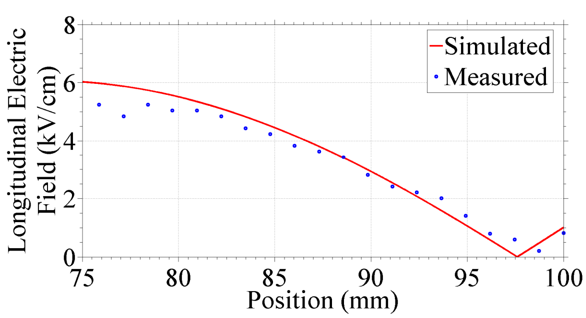

Figure 9. Simulated and optically measured longitudinal electric field magnitudes in the PT. Only the last 25 mm were measured due to the size of the vacuum chamber window. Simulated parameters correspond to a parallel 10 GΩ, 0.04 pF load.

IV. SUMMARY

A lithium niobate piezoelectric transformer was operated with a thermionically-emitted electron beam load at vacuum pressures between 10^{-6} and 10^{-5} Torr. Thermionic filament currents between 2.0 and 2.5 A_{DC} were used to heat the tungsten alloy filament. Output electrical and input mechanical Q-values were measured using a 2.3 A_{DC} filament current. An optical diagnostic was used to measure the stress and electric field within the PT. The PT had a peak output power of 29 mW with an average output power of 0.7 mW. Further analysis will be required to determine the effects of varied beam currents and capacitance to the beam source and vacuum chamber.

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